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A DESIGN PROCEDURE FOR A SCOUR JET ARRAY. (U)
SEP 80 J A BAILARD

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INTRODUCTION

Many Navy harbor facilities are located in estuarine environments and are subject to heavy shoaling. Rivers flowing into these areas carry large quantities of clay-sized sediments, which flocculate upon reaching the higher salinity estuarine waters. These flocculants are preferentially deposited in quiet water areas such as pier and berthing facilities. Removal of this material by dredging represents a continual Navy expense.

A recent study of dredging problems in Navy harbors by Malloy (1980) concluded that the Navy currently dredges 9.95 M cubic yards of sediment each year. Ninety-two percent of this sediment is cohesive, consisting primarily of flocculated clays. The Navy's cost for this dredging is currently estimated at \$30 M/yr. More significantly, dredging costs are projected to rise dramatically in the future due to rising energy costs and Federal environment restrictions.

Recognizing the magnitude of this problem, the Naval Facilities Engineering Command (NAVFAC) initiated a program in 1975 to develop a number of innovative sediment management techniques to reduce the Navy's dredging burden. The work was sponsored by NAVFAC Code 03 as part of the environmental protection program at CEL. The primary intent of the program was to concentrate on cohesive sediment control due to its importance in Navy harbors. A number of different concepts were explored in the laboratory including air curtains, water curtains, passive curtains and scouring water jets (Van Dorn et. al. 1975, 1977). On the basis of these experiments, the passive curtain and scouring water jet concepts were judged most promising. A series of prototype experimental systems based on these two concepts was designed by Scripps Institution of Oceanography (SIO) and tested at Mare Island Naval Shipyard (MINSY) (Van Dorn, et. al. 1978, 1980). The success of these tests has encouraged further engineering development of both concepts, with the eventual goal of installing operating systems in all candidate Navy harbors.

Anticipating the deployment of these systems in a wide variety of harbors, a study was requested of the Civil Engineering Laboratory (CEL) to develop a general design procedure for a scour jet array. The scour jet array was selected because of its advanced state of development relative to the passive curtain system. The objective of the study was to develop a design procedure which would lead to an optimum preliminary design for a particular site. This technical note, consisting of several parts, documents the above study. First, the scour jet array concept is discussed along with a description of its components and method of operation. This is followed by sections on general sedimentation processes, turbulent jet characteristics and pumping system economics. Next, a computer-assisted optimization procedure is introduced detailing the selection of a single system having the smallest annual cost. Finally, the completed design procedure is discussed and a site specific example is included.

SYSTEM DESCRIPTION

A scour jet array consists of a linear array of water jets, located along a quay wall, pier or other berthing facility, (Figure 1). In addition to the jets and associated piping, components of the array include a water pump, a series of automatic control valves and a control system which sequences the jets with the tidal currents in the area.

The particular component configuration shown in Figure 1 is only one of several possible configurations. Other configurations include a submerged manifold pipe with submerged control valves, an exposed manifold pipe with submerged control valves or a completely submerged system including a submerged pump. For the purposes of this note however, it is assumed that the system appears as shown.

Another source of variation is the type of material used in the fabrication of the various components. Generally, there is a trade off between a higher initial cost and an increased longevity as more corrosion resistant materials are considered. Although the system alternatives are almost limitless, for this study it will be assumed that the pump, pipe and valves are either cast iron or steel. As previously

stated, the emphasis of this study is to establish a rational design procedure. If other configurations or materials are desired, the design procedure can be modified to accommodate them.

System variables include the jet diameter, the number of jets, the pipe diameter, the array length, the desired scour radius, the pump flowrate, the pump pressure and the jet duty cycle. It will be shown that the number of physical equations needed to describe a jet array is one less than the number of jet array variables. As a means of obtaining closure, the concept of an optimum system will be introduced, with the optimization parameter being the smallest annual cost.

SEDIMENTATION PROCESSES FOR CLAY SEDIMENTS

The processes of scour and deposition of flocculated clays in estuarine environments are not well understood. Much of the problem lies in the complexity of the sediment itself, which changes properties as a function of time after deposition. Van Dorn et. al. (1977), summarizing laboratory studies by Krone (1962, 1974), gave the following deposition sequence. River born clay mineral particles are initially dispersed due to a sheathing of their electrically charged surfaces by water molecules, rendering them mutually repulsive. Upon reaching the more saline estuarine waters, the molecular sheathing is partially destroyed, resulting in a mutual attraction and eventual flocculation. The flocculants have a significantly higher fall velocity than the individual clay particles, thus encouraging rapid deposition in quiet water areas.

Deposition occurs as a loosely structured layer of unconsolidated flocculents having an initial solids concentration of 10-15 kg/m³ and a shear strength of approximately 0.06 nt/m². After deposition the layer rapidly compacts, reaching a final solids concentration of 300-400 kg/m³ with a correspondingly higher shear strength. In a navigation channel subject to significant tidal action, deposition occurs during slack water. The freshly deposited sediment is then only partially re-suspended during the following phase of the tidal cycle, due to the rapid consolidation process mentioned above.

In many areas, the rate of deposition is found to vary -- both in time and space. Spatial variations are related to variations in the local water circulation and the bottom shear stress. Similarly, the rate of sediment deposition reflects the seasonal variations in the local abundance of suspended sediment. The latter has been found to be related to the river discharge. Another factor which affects the local rate of deposition is the salinity, which varies with river discharge and relative position within the estuary. Generally speaking, flocculation only occurs when the salinity exceeds approximately 10 parts per thousand (ppt).

From an energetics standpoint, it is clearly advantageous to re-suspend any newly accumulated sediment as soon as possible. It can be shown (see section on Equations) that the power expended by a water jet increases with the 1.9 power of the shear stress at a given distance from the jet. Thus, in a tidally dominated area, it will be assumed that a scour jet array will be operated during every ebbtidal cycle. The shear stress required to adequately scour daily deposition is difficult to estimate. However, based on field experiments it appears that 0.4 nt/m^2 is adequate. More generally, the minimum stress level is also related to the duty cycle time of the jet. Using incomplete field experience, 12-minute per ebbital cycle appears adequate for a 0.4 nt/m^2 stress level.

PHYSICAL SYSTEM EQUATIONS

The principle of operation for a scour jet array is to re-suspend a freshly deposited layer of loosely consolidated sediment using a submerged water jet. It is important then to understand the mechanics of a turbulent wall jet so that the shear stress distribution associated with the jet can be predicted as a function of the critical jet parameters. To this end, Van Dorn et. al. (1975 and 1977) performed a series of laboratory experiments to determine both the shear stress distribution and the scouring capability of submerged wall jets as a function of the jet diameter and discharge velocity.

Van Dorn et. al. tested a number of jet nozzle configurations, but eventually concentrated on a simple circular nozzle positioned horizontally and slightly raised from the bed. Two types of tests were conducted. First, scour patterns made in freshly deposited layers of diatomaceous earth were measured for varying jet flowrates and nozzle diameters. Second, as a means of correlating the scour measurements with the bottom shear stress levels, the shear stress distribution associated with a single-sized jet was measured as a function of the jet discharge rate. As a result of these tests the following dimensionless equation was proposed by Jenkins et. al. (1980):

$$\frac{\tau_o}{\rho} = 120 U_o^2 \left(\frac{U_o d}{\nu} \right)^{-0.4} \left(\frac{r}{d} \right)^{-2.4} \quad (1)$$

where τ_o is the bottom shear stress, ρ is the fluid density, ν is the kinematic fluid viscosity, U_o is the jet velocity, d is the jet diameter and r is the distance from the jet nozzle. Equation 1 indicates that the shear stress at a given distance from the nozzle is a function of the discharge velocity, the jet velocity and the fluid properties. The pressure drop through the jet is predicted by:

$$U_o = c \sqrt{2 \Delta p / \rho} \quad (2)$$

where Δp is the pressure drop and c is a dimensionless discharge coefficient. For a properly designed nozzle, c has been found to be approximately equal to 1 and this value will be assumed throughout the note. The number of jets in the array depends on the separation distance of the jets, ΔL , which is assumed to be equal to:

$$\Delta L = r / 3.3 \quad (3)$$

Equation 3 is specified to provide a 10% overlap in the scour patterns between adjacent jets (Van Dorn et. al., 1975). The number of jets in an array becomes:

$$n_j = L/\Delta L \quad (4)$$

The jet discharge rate, q , is related to the jet discharge velocity and diameter by:

$$q = \frac{\pi d^2}{4} U_o \quad (5)$$

Similarly, the flowrate is related to the pipe velocity, V by:

$$q = \frac{\pi D^2}{4} V \quad (6)$$

where D is the pipe diameter. For simplicity, the pipe velocity will be assumed to be a constant and equal to 2.5 m/sec. This value has been specified by La Que (1975, p 150) to be the highest velocity which does not produce an excessive rate of corrosion for steel pipe.

Another equation which is important in the design of a scour jet array is the Darcey-Weisbach head loss equation (Vennard 1961, p 280) e.g.:

$$h_L = f \frac{\ell}{D} \left(\frac{V^2}{2g} \right) \quad (7)$$

where h_L is the head loss in height of water, ℓ is the length of pipe, D is the pipe diameter, g is gravity and f is the pipe friction factor. The latter may be estimated from the pipe velocity and roughness using the Moody diagram e.g., Vennard (1961, p. 287). The minor head losses associated with piping bends and fittings can be estimated by an equation similar to the Darcey-Weishbach equation (Vennard 1961, p 309) e.g.:

$$h_{L_m} = K_L \frac{V^2}{2g} \quad (8)$$

where K_L is an empirically determined dimensionless coefficient.

The hydraulic power produced by the pump, ω_p , is given by:

$$\omega_p = \left(\rho g \sum_i h_L + \Delta p \right) q \quad (9)$$

The power produced by the motor in driving the pump, ω_m , is related to ω_p by:

$$\omega_m = \omega_p / \eta_p \quad (10)$$

where η_p is the pump efficiency, commonly ranging from approximately 0.8 to 0.9. Similarly, the electric power consumed by the motor, ω_e , is given by:

$$\omega_e = \omega_m / \eta_m \quad (11)$$

where η_m is the efficiency of the motor and is approximately equal to 0.9. For purposes of latter calculations, it is convenient to relate ω_e directly to ω_p by combining equations 9 and 10 yielding:

$$\omega_e = \frac{\omega_p}{\eta_p \eta_m} \quad (12)$$

Finally, it has been shown (Hicks 1957, p 251) that the product $\eta_p \eta_m$ is generally a function of the hydraulic power of the pump, ω_p . This relationship may be expressed:

$$\eta_p \eta_m = 0.577 + 0.153 x - 0.025x^2 - 0.004x^3 \quad (13)$$

where $x = 1.48 \log \omega_p - 2.0$

Examining Equations 1 through 13, one finds that there are 12 independent equations and 13 unknowns. Consequently, the system is mathematically indeterminant. This is intuitively obvious from Equation 1 because different combinations of U_o and d can be used to generate the

same shear stress distribution. In order to solve for a unique system, an additional criterion is needed. As we will see in the next section, one solution is to select the system with the smallest annual cost.

ECONOMIC ANALYSIS

A complete economic analysis of a scour jet array is beyond the scope of this note. For present purposes, a limited analysis is sufficient, based on the techniques and concepts outlined in NAVFAC P-442 (1975). For simplicity the annual cost of a scour jet array is assumed to be composed of an initial capital cost and a recurring yearly operating cost. Maintenance costs are assumed to be negligible. A fundamental precept of an economic analysis is that all costs incurred throughout the lifetime of a system must be compared relative to a single point in time. The rationale is that due to the time-value cost of money, money spent today is more valuable than the same money spent in the future. In economic terms, the present value, PV, of a single future expenditure, F_n , is a function of the prevailing discount rate, i , and the number of years in the future in which it is made, n . Thus,

$$PV = F_n \left[\frac{1}{(1 + i)^n} \right] \quad (14)$$

In the present case, i is assumed to be equal to 0.10 in accordance with NAVFAC P-422 (1975) guidelines. Note that the discount rate, i , represents the net rate of return after inflation. If the cost associated with F_n is subject to a differential rate of inflation (or deflation), i_d , relative to the rate of inflation of most goods and services (e.g., energy costs), then Equation 14 must be modified to:

$$PV_d = F_n \left[\frac{1 + i_d}{1 + i} \right]^n \quad (15)$$

Again, in accordance with NAVFAC P-442 (1975) guidelines, i_d is assumed to be equal to 0.03. Equations 14 and 15 describe the present value of a single future cost. If recurring costs occur on a yearly basis, such as yearly operating costs, then the present value of a series of uniform costs for n years is:

$$PV = F_n \sum_{j=1}^n \left(\frac{1}{1+i} \right)^j \quad (16)$$

and

$$PV_d = F_n \sum_{j=1}^n \left(\frac{1+i_d}{1+i} \right)^j \quad (17)$$

For simplicity, the summed quantities in Equations 16 and 17 are termed the cumulative uniform series discount factor and escalation discount factor, respectively:

$$pvf = \sum_{j=1}^n \left(\frac{1}{1+i} \right)^j \quad (18)$$

and

$$pvf_d = \sum_{j=1}^n \left(\frac{1+i_d}{1+i} \right)^j \quad (19)$$

In the case of a scour jet array, the present value of the system, PV_{sys} , is:

$$PV_{sys} = C_c + pvf_d C_e \quad (20)$$

where C_c is the initial or capital cost of the system and C_e is the uniform yearly operating cost of the system. The latter is assumed to reflect a constant yearly consumption of electricity.

The uniform annual system cost, C_a , may be related to the present value of the system by:

$$C_a = \frac{PV_{sys}}{pvf} \quad (21)$$

thus

$$C_a = \frac{C_c}{pvf} + \frac{pvf_d}{pvf} C_e \quad (22)$$

In the previous section, the system of equations describing a scour jet array were shown to be indeterminant, indicating that a multitude of different scour jet systems, each having different capital and energy costs, would provide the same shoaling protection for a particular area. Equation 22, however, allows one to compare the annual cost of each candidate system. If an optimum system is defined as that system with the lowest annual cost, then Equation 22 along with Equations 1 through 13 provide a closed form solution for a scour jet array.

Before further discussion of the optimization procedure, it is of interest to consider the economic attractiveness of a particular system. One measure of a system's economic worth is the savings investment ratio (SIR). In the case of a scour jet array, the SIR may be computed as:

$$SIR = \frac{pvf_d(C_d L r - C_e)}{C_c} \quad (23)$$

where the dredging cost C_d (\$/m² - yr) reflects the present cost of keeping a unit area of bottom free of deposition for 1 year using conventional means of dredging. Note that due to the energy intensiveness of dredging, it is assumed that C_d has a differential rate of inflation equal to that of electricity. Note also that C_d is the product of the local yearly rate of deposition (m/yr) and the per unit volume cost of dredging (\$/m³). As a result, C_d is strongly site specific.

Equations 22 and 23 may be combined to yield the SIR as a function of the dredging cost, the capital cost and the annual cost, i.e.:

$$SIR = 1 + \frac{pvf_d C_d L r - pvf C_a}{C_c} \quad (24)$$

Finally, another useful concept associated with the SIR is the payback period n' . The payback period is defined as the number of years until the present value of the system savings equals the initial capital cost of the system. In other words, n' is defined by:

$$\sum_{j=1}^{n'} \left(\frac{1 + i_d}{1 + i} \right)^j = \frac{pvf_d}{SIR} \quad (25)$$

Thus, n' is a function of the discount rate, i , the system lifetime, n , and the SIR. Figure 2 shows the payback period, n' , as a function of the savings investment ratio assuming a 10-year lifetime, a 10% discount rate and a 3% differential rate of inflation for electricity and dredging costs.

COMPUTER-AIDED OPTIMIZATION

The two previous sections provide the basic set of equations necessary for selecting an optimum scour jet array design. Unfortunately, the selection procedure requires computing the annual cost of a wide range of candidate systems. This procedure, however, may be routinely performed with the use of a computer. Before developing the necessary computer code, it is necessary to be able to characterize the costs of various system components as a function of system geometry and operating conditions.

The economics of pumps and their associated equipment is relatively simple. Hicks (1957) suggests that the installed cost of pumps and driving motors can be related to their respective powers, and the installed costs of pipe, valves and fittings can be related to their respective sizes. Accordingly, a number of manufacturers were contacted to obtain cost estimates at the components. In addition, installation costs were estimated from the Dodge Manual (1978) after allowing a 20% adjustment for inflation. Figures 3 and 4 show the results of this procedure,

where the costs of pumps and motors are shown as a function of power and the costs of pipe and valves are shown as a function of pipe diameter. On the basis of these figures it was found that;

$$\text{\$pump} = 365 \omega_p^{2/3} \quad (26)$$

and

$$\text{\$motor} = 62.0 \omega_m \quad (27)$$

where ω_p and ω_m are expressed in kW. Similarly, it was found that the cost of schedule 80 steel pipe per meter, installed with fittings, was:

$$\text{\$pipe/m} = 974 D^{1.09} \quad (28)$$

The per unit cost of an installed cast iron pneumatic pinch valve was:

$$\text{\$valve} = 10366 D^{1.47} \quad (29)$$

where the pipe diameter D is measured in meters. Note that other types of control valves such as pneumatically actuated butterfly valves are similarly priced. In addition, the cost of large diameter (~ 0.20 m) schedule 80 PVC pipe is similar to that of steel.

The cost of a control system for a scour jet array also varies with the size of the system. Although a wide variety of control systems are available, it is assumed that it consists of a general purpose modular control system (e.g., Pro Log Series 7000) whose cost can be estimated as:

$$\text{\$controller} = 1725 + 295 \frac{n_j}{8} \quad (30)$$

where n_j is the number of jets in the array.

Equations 1 through 30 provide the basis for a computer-aided design procedure for a scour jet array. Figure 5 shows a simplified flow diagram of the computer code. The input variables include both site and system specific information. The former are: the scour shear stress, τ_o ; the number of days of sedimentation per year, n_{sed} ; the length of the area to be protected, L ; the width of the area to be protected, r ; and, the cost of electricity, e_{elc} . System inputs include the generic type and material of the various components (discussed in System Description) and the general system lifetime, n . The output from the computer code consists of estimates of the optimum jet diameter, pipe diameter, pump flowrate and head. In addition, the system's annual cost, capital cost and SIR are calculated. A listing of the complete computer code is included in Appendix A.

Recognizing that more general design guidelines are often desired in the preliminary stage of a design, it was decided to develop a set of figures for an alternative graphic design procedure. The assumptions used in developing the figures were that the bed shear stress is 0.4 nt/m^2 at the design scour distance r , the duty cycle time per jet is 12 min twice per day, sedimentation is continuous throughout the year, the discount rate is 10%, the differential rate of inflation for electricity is 3% and electricity costs are $\$0.05/\text{kW-hr}$. These assumptions were judged to be representative of present average conditions around the nation.

The results of the above procedure are contained in Figures 6 through 12. Figure 6 shows the optimum jet diameter as a function of the array length and the scour radius. By optimum, it is meant that this jet diameter defines a system having the lowest annual cost for the specified values of L and r . With d thus defined, Equations 1 through 30 may be used to calculate all the other pertinent system information, as discussed in the section on Equations. Figures 7 and 8 show the capital costs and annual costs associated with the optimum systems defined by Figure 6. These figures show that system costs increase sharply as the scour radius becomes large due to increased power consumption.

Figures 9 through 12 show the savings investment ratio (SIR) as a function of the array length, L , and the scour radius, r , for dredging costs of \$4, \$8, \$12 and \$16/m² respectively. As expected, these figures demonstrate that for a given length and width of protected area, a scour jet array becomes more economical (larger SIR) as the conventional dredging costs for the area increase. In addition, for a given scour radius there is generally an optimum array length which has the largest SIR. This suggests that if a very long area is to be protected, it may be more economical to protect the area with several subsystems. In practice, the length of a scour jet array may be constrained first by the limited duration of the ebbtidal cycle. Figures 6 through 9 also show that for a given length jet array, there is a limited range of scour radii that are economical i.e., all those that have a SIR greater than 1. Less obvious perhaps is that for a given length array, it is most economical to design a system with a scour radius yielding the largest SIR. In other words, even if a larger scour radius is desired, it is more economical to use the optimum radius and conventionally dredge the rest of the area. Similarly, if a smaller distance is desired, the added scour distance more than pays for itself. Figures 6 and 7 show that for average conditions, the dredging cost per square meter of bottom must exceed approximately \$6 for a scour jet array to be economical. As an example, for a unit volume dredging cost of \$3/m³, the deposition rate must be greater or equal to 2 m/yr. These costs (benefits) however, do not reflect any added benefits such as the reduced costs associated with having to move vessels during dredging operations. Another benefit at some locations is a reduced labor cost for divers who must use water jets to free a berthed vessel from mud accumulations prior to the vessel's departure. Finally, it should be noted that the SIR is sensitive to the assumed electricity cost. At present, the per unit cost may vary by a factor as great as 2 or 3. Moreover, if significant sedimentation occurs only during part of the year, the reduced operating time also increases the SIR. As a consequence, in most instances these figures should be used only as guidelines to determine if a more detailed study is warranted.

DESIGN PROCEDURE

After identifying a potential site, the first step in designing a scour jet array is to gather the appropriate site data. As discussed, this includes the total array length, the desired scour radius, the yearly rate of deposition and its seasonality, the cost of electricity, the unit volume cost of dredging and the shear stress level required to scour the bottom. While it is anticipated that the latter may be site specific, a value of 0.4 nt/m^2 is presently recommended.

The next step in the design process is to select the generic component types and their materials. As discussed earlier, the number of system alternatives is almost limitless. However, the present design procedure assumes a specific system configuration, component type and material. If deviations from the assumed system are desired, the design procedure can be changed to accommodate them. In general, however, this would require developing new cost estimates for the various components and a re-calculation of Figures 6 through 12.

Once the site and system inputs have been selected, these should be compared to the "average" inputs used to develop Figures 6 through 12. If the inputs are sufficiently similar, then the appropriate figures can be used to determine the optimum values of L and r that produce the largest SIR. This procedure, however, is subject to the constants of the site (i.e., L cannot exceed the total length of the protected area and the number of jets cannot exceed the number which may be operated in a single ebbtidal cycle). In practice, the optimum array length will usually be maximized, subject to constraint by either the ebbtidal cycle duration or the total length of the desired array. This is suggested by Figures 9 through 12, which show increasing SIR with increasing L . After determining L , r may be varied to maximize the SIR. If dredging costs are the only consideration, then r should not exceed that value which maximizes the SIR. If a larger r is desired, it would be more economical to dredge the extra area by conventional means. If a smaller r is desired, it still pays to scour the extra area. If the system inputs are not similar to those used to generate Figures 6 through 12,

then a new site specific figure must be constructed using the computer code listed in Appendix A. The new figure can then be used in the above procedure.

At this point, all the necessary inputs are defined for the computer optimization code (see Appendix A). Output from the program yields the system geometry, flowrate and pressures. Alternatively, if the input conditions are approximately equal to the "average" conditions discussed in the section on Computer-Aided Optimization, then Figures 6, 7 and 8 may be used to estimate the optimum jet diameter, the system capital cost and the system annual cost. The optimum jet diameter may then be used with Equations 1 through 9 to solve for the complete system geometry, flowrate and pressures. Estimates of these quantities complete the preliminary design process. The next step in the design process is to select the various components and ensure their compatibility. This, however, is beyond the scope of this note.

As an example of the above design procedure, preliminary design of a proposed scour jet array at Mare Island Naval Shipyard is included. Following a site survey, it was determined that a 762 m long quay wall was to be protected out to a distance of approximately 15 m. Protection is required for approximately 244 days of the year, since almost no deposition occurs during the late summer and fall. It is assumed that the jet duty cycle is 12 min operated twice daily during ebbside. The total duration of the ebbside cycle is 360 minutes. Based on field tests, a minimum scouring stress of 0.4 nt/m^2 is assumed. In addition, electricity costs are $\$0.025/\text{kW-hr}$ and dredging costs are $\$12/\text{m}^2$. Finally, it is assumed that the pump and valves are cast iron (with bronze fittings) and the pipe is schedule 80 steel. A system life of 10 years is assumed, as is a discount rate of 10% and a 3% differential rate of inflation for electricity.

The above specifications are sufficiently different from the "average" conditions previously discussed so that Figure 13 describing the SIR as a function of L and r was developed using the computer code listed in Appendix A. Figure 13, shows that for a scour radius of approximately 15 m, the SIR increases with increasing array length. Based on this evidence, the array should be as long as possible and subject to the

limited duration of the ebbtidal cycle. Since each jet has a duty cycle of 12 min, the maximum number of jets which can be operated with one system is 30. The total array, however, consists of approximately 168 jets, thus the quay wall will be protected by 6 subsystems, each consisting of 28 jets and having a length of 126 m. Figure 13, also shows that the maximum SIR for an L of 126 m occurs when $r = 15$ m, a fortunate coincidence. Thus, each subsystem will have an L of 126 m and an r of 15 m.

Using the above program inputs, the computer code listed in Appendix A predicted an optimum jet diameter of 0.064 m, a pipe diameter of 0.188 m, a water flowrate of $0.069 \text{ m}^3/\text{sec}$, a total pump head of 27 m, a motor power of 31 kW, a capital cost of \$55,000 per subsystem and an annual cost of \$11,000 per subsystem (Appendix B). The estimated SIR is 2.66; with a payback time of 3.3 yr. Based on these estimates, it is advised that the closest nominal-sized pipe and motor be chosen, thus the pipe should be 0.203 m (8 in.) and the motor should be 37.3 kW (50 hp).

The component sizing and operating parameters for the system have thus been established. At this point, a final system design must be made, where the actual components are selected and their compatibility is checked. Depending on the size of the system, if there is a significant variation in the pressure at each jet, it may be necessary to fine tune the size of each jet so that the pump always operates within its design range. This procedure is relatively easy to accomplish using the equations discussed previously.

CONCLUSIONS

A design procedure has been developed to aid in the preliminary design of a scour jet array of arbitrary size. The procedure is based on a combined physical and economic analysis of a scour jet array. The economic analysis was necessary because the basic system is indeterminate, i.e., a multitude of systems are able to scour a given area of bottom. An optimum system was defined as the system which had the lowest annual cost.

In a related development, it was found that the savings investment ratio (SIR) is a function of the system length, scour radius and dredging cost. Generally speaking, for "average" conditions (defined in the Computer-Aided Optimization) a scour jet array does not become economically attractive ($SIR \geq 1$) until the dredging cost of bottom exceeds \$6/m². Moreover, the design procedure allows one to optimize the overall dimensions of the protected area so that the largest possible SIR is obtained.

Based on the results of the present study, it is recommended that scour jet arrays be installed at all candidate sites which are either difficult to dredge by conventional means or are subject to sedimentation rates in excess of 2-3 m/yr. Examples of the latter would include Mare Island Naval Shipyard and Charleston Naval Base.

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CONCEPTUAL JET ARRAY

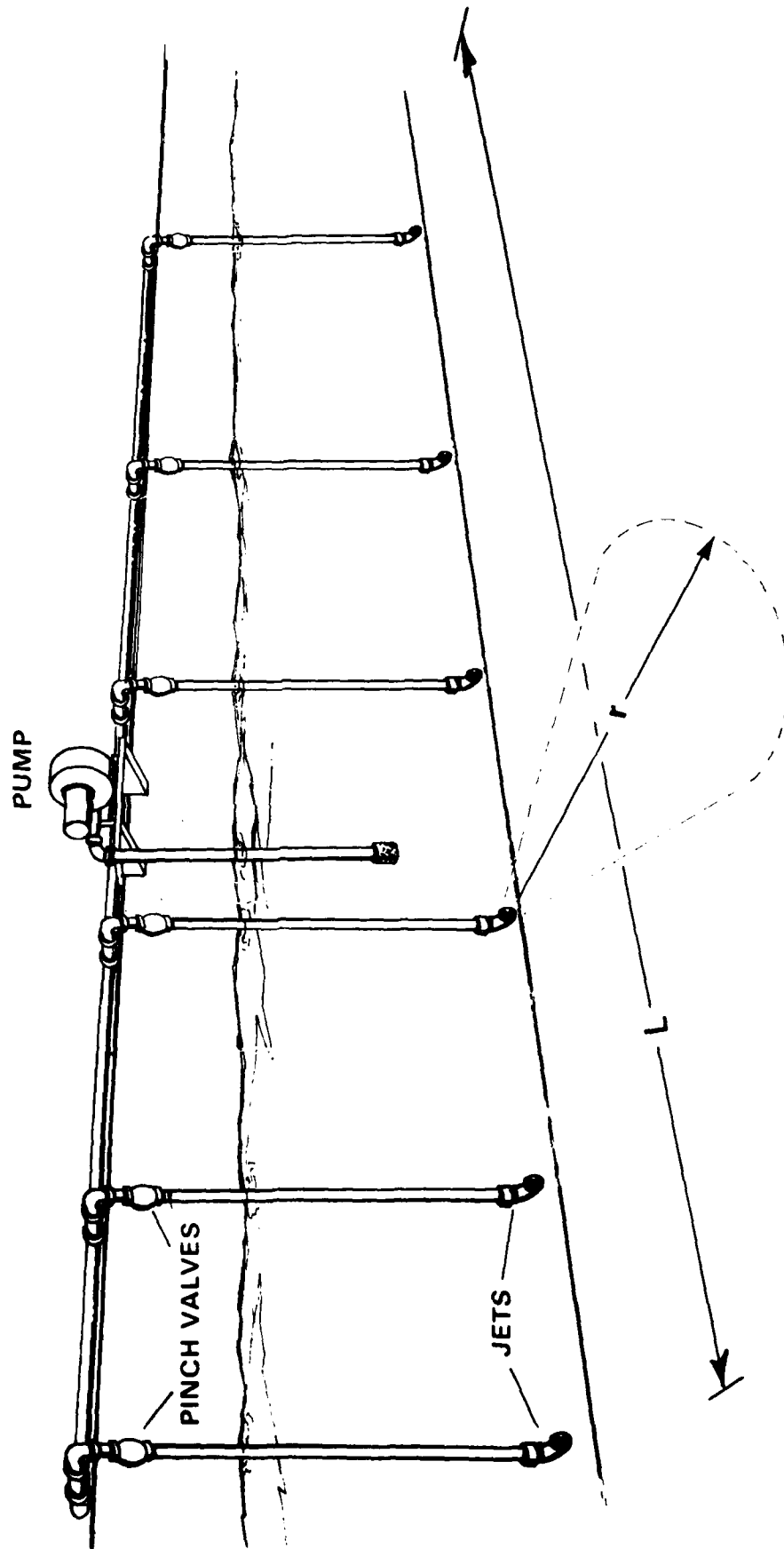


Figure 1. Conceptual sketch of a scour jet array with a length L and a scour radius r .

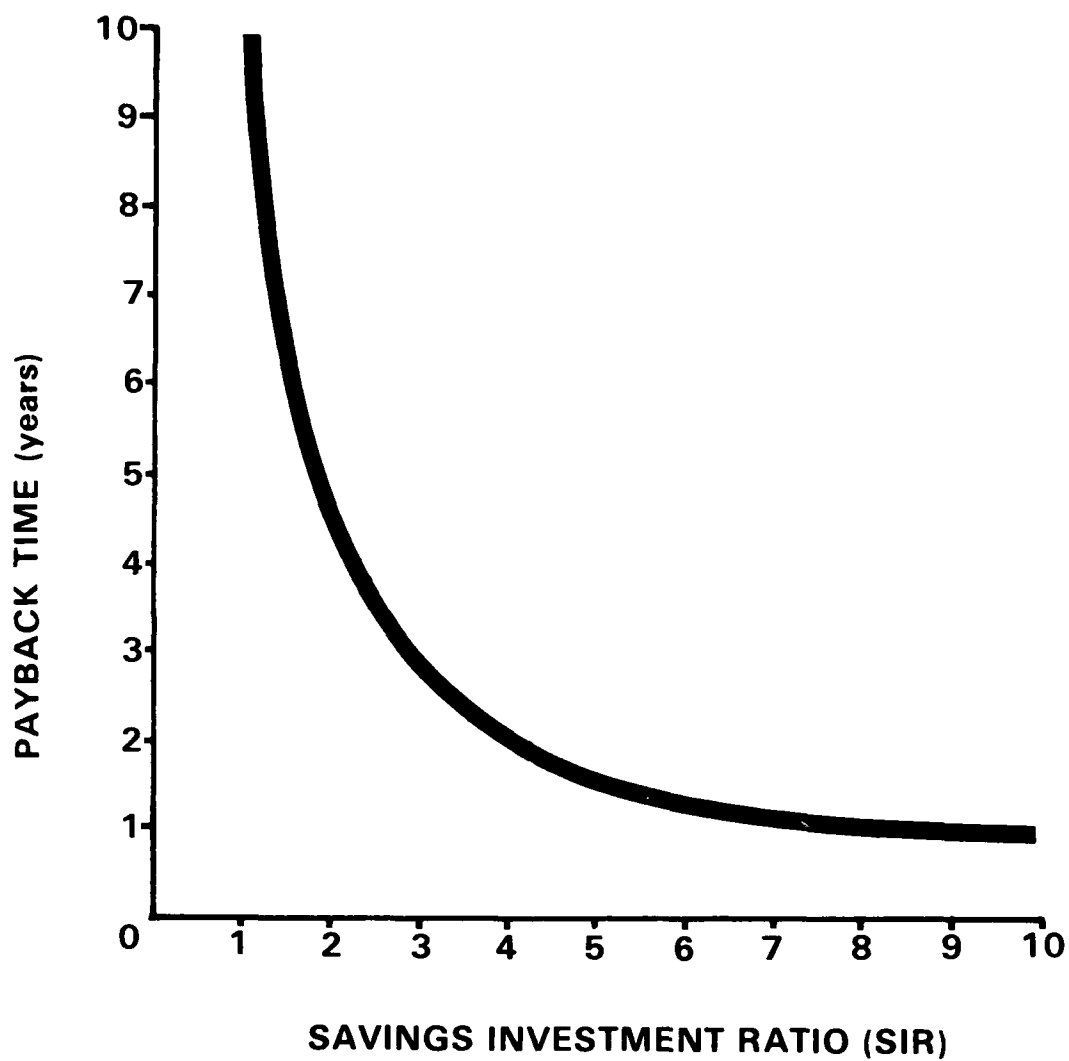


Figure 2. Payback time versus savings investment ratio assuming a 10 year lifetime, a 10% rate of return and a 3% differential rate of inflation for electricity.

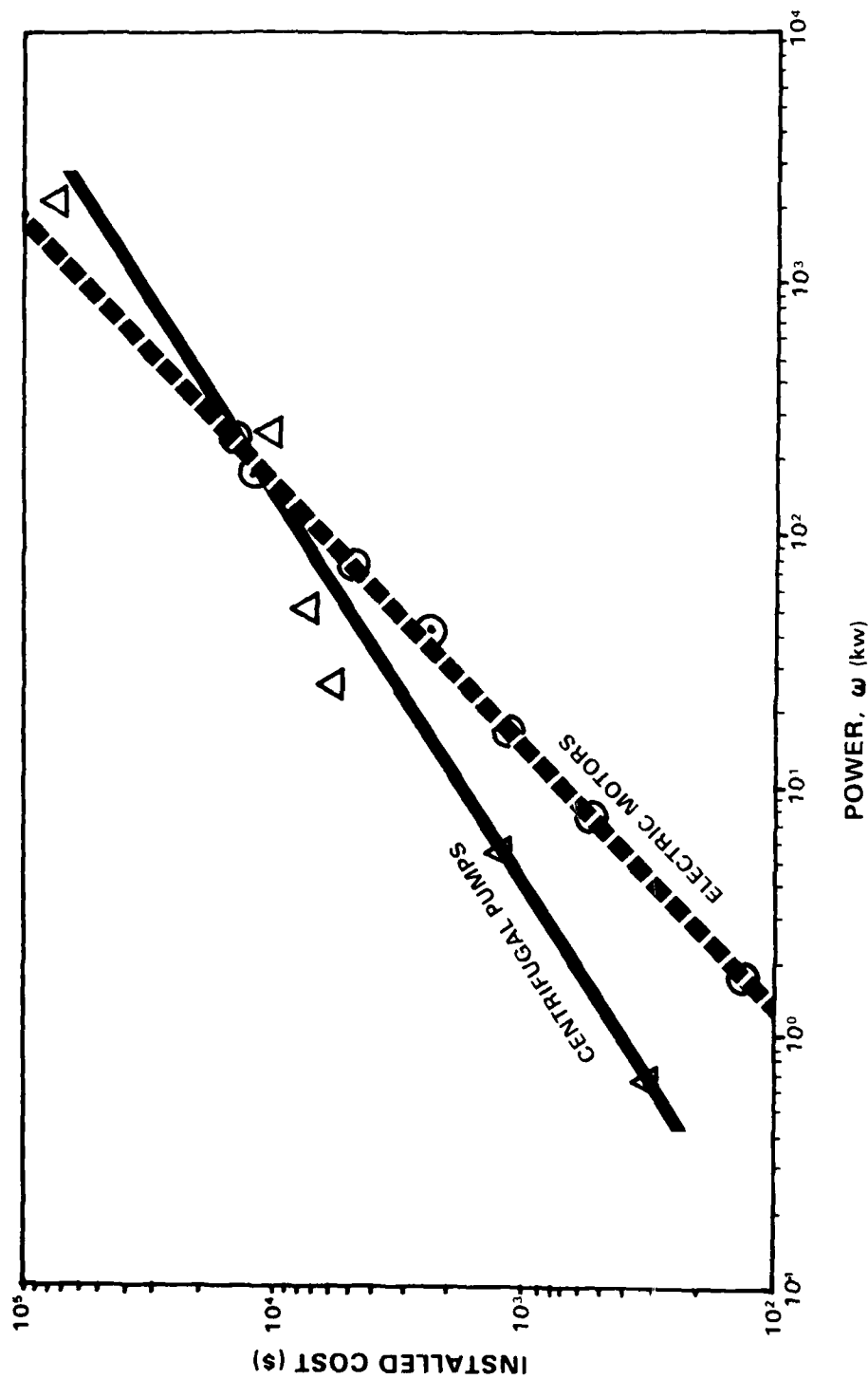


Figure 3. Installed cost of centrifugal pumps and electric motors as a function of power.

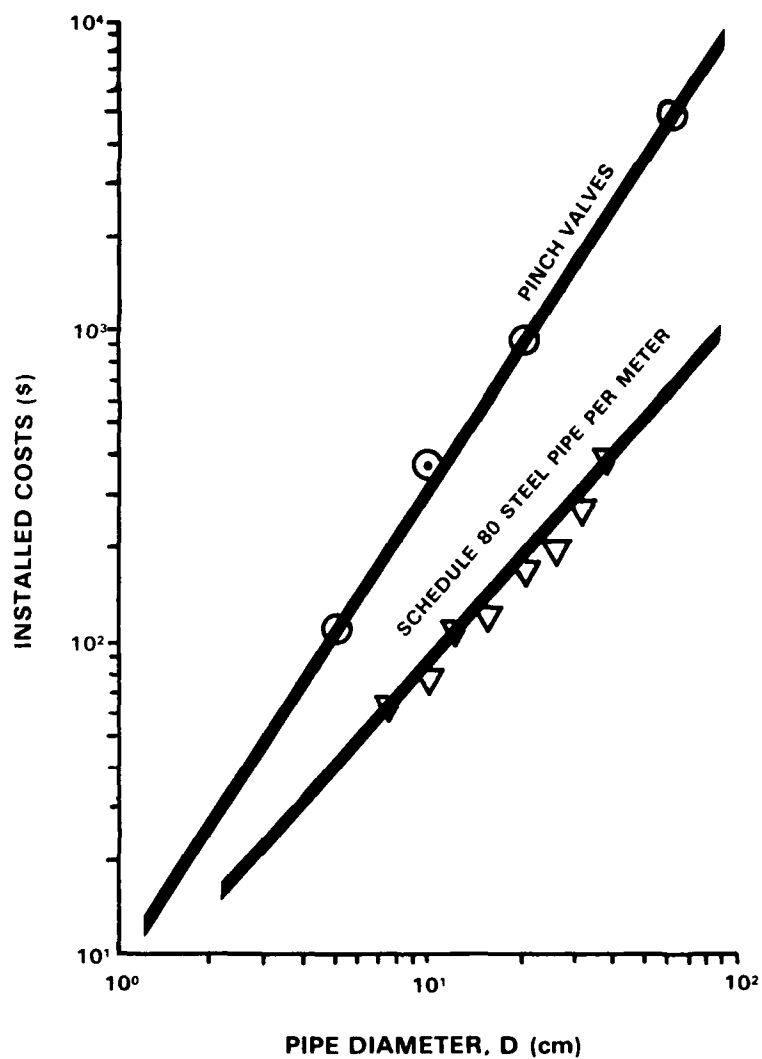


Figure 4. Installed cost of steel pipe and cast iron pinch values as a function of pipe diameter.

COMPUTER FLOW DIAGRAM

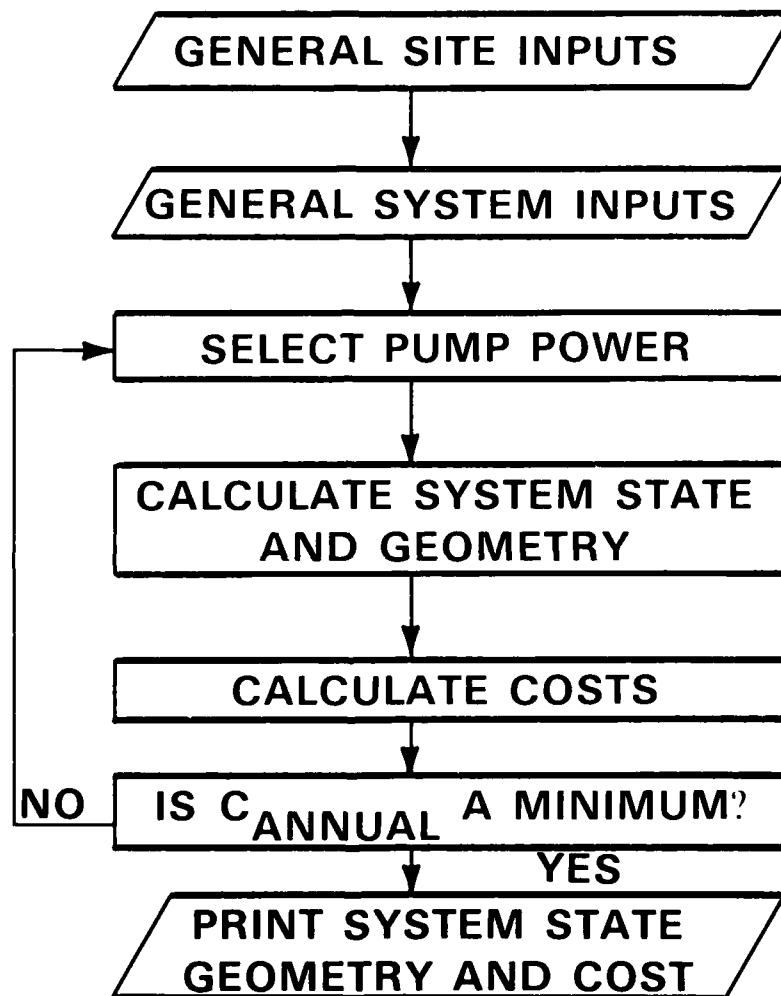


Figure 5. Flow diagram for computer code which selects an optimum scour jet array.

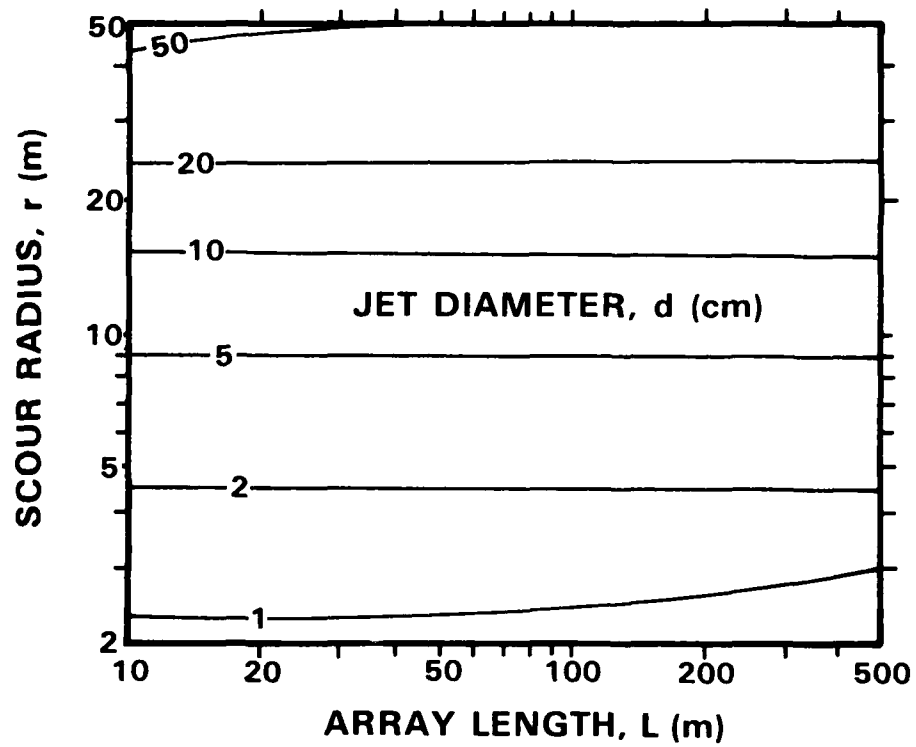


Figure 6. Jet diameter versus scour radius and array length for optimal jet arrays.

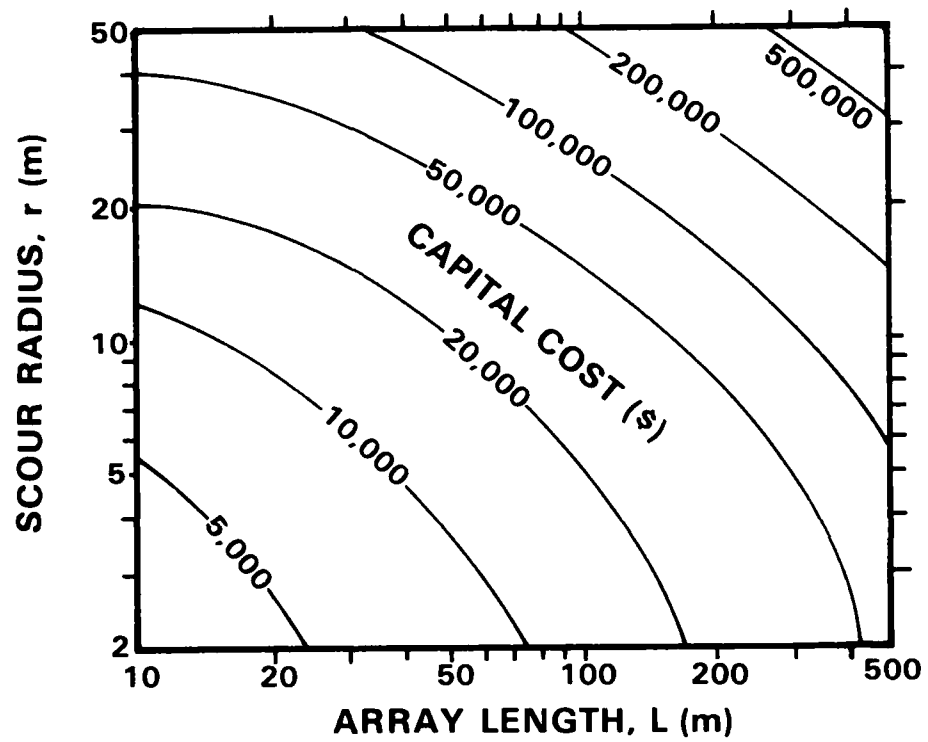


Figure 7. Capital cost versus scour radius and array length for optimal jet arrays.

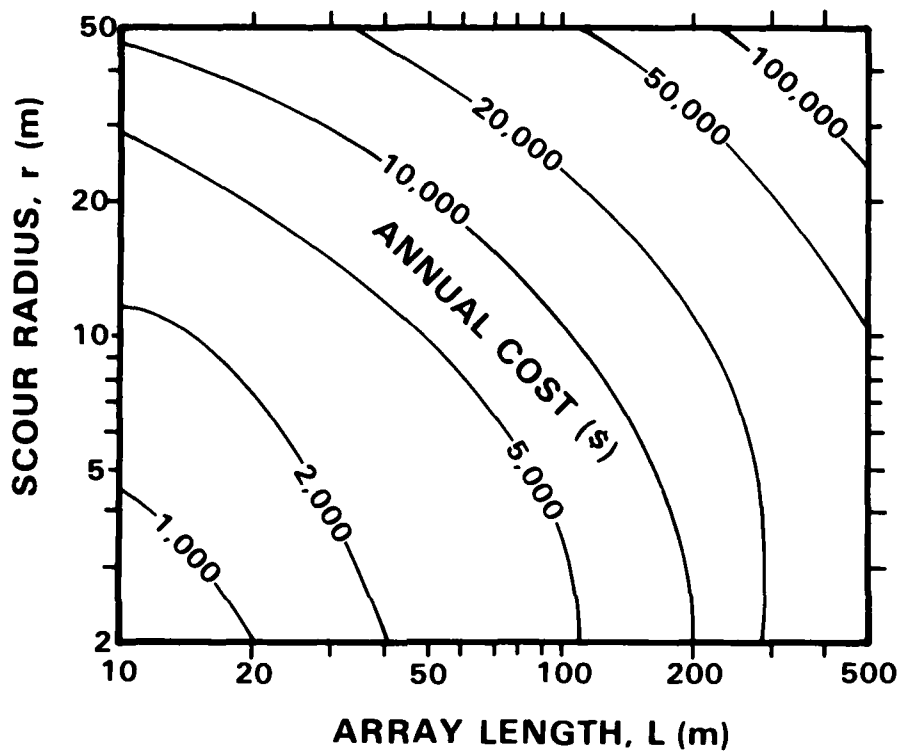


Figure 8. Annual cost versus scour radius and array length for optimal jet arrays.

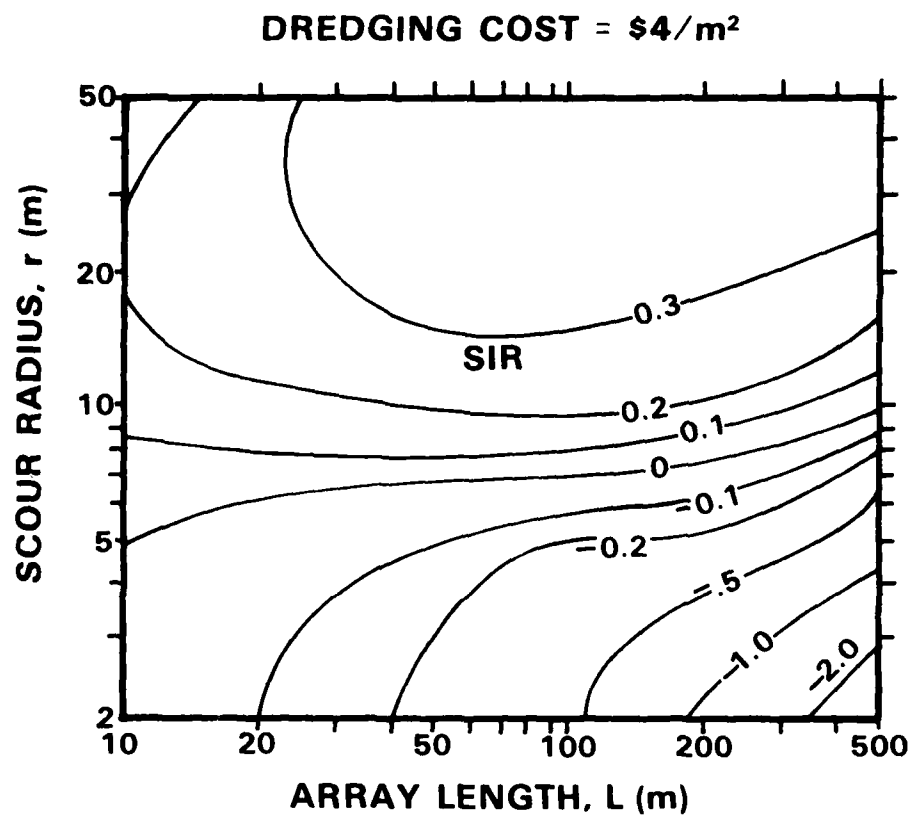


Figure 9. Savings investment ratio as a function of scour radius and radius length assuming a dredging cost of \$4/m².

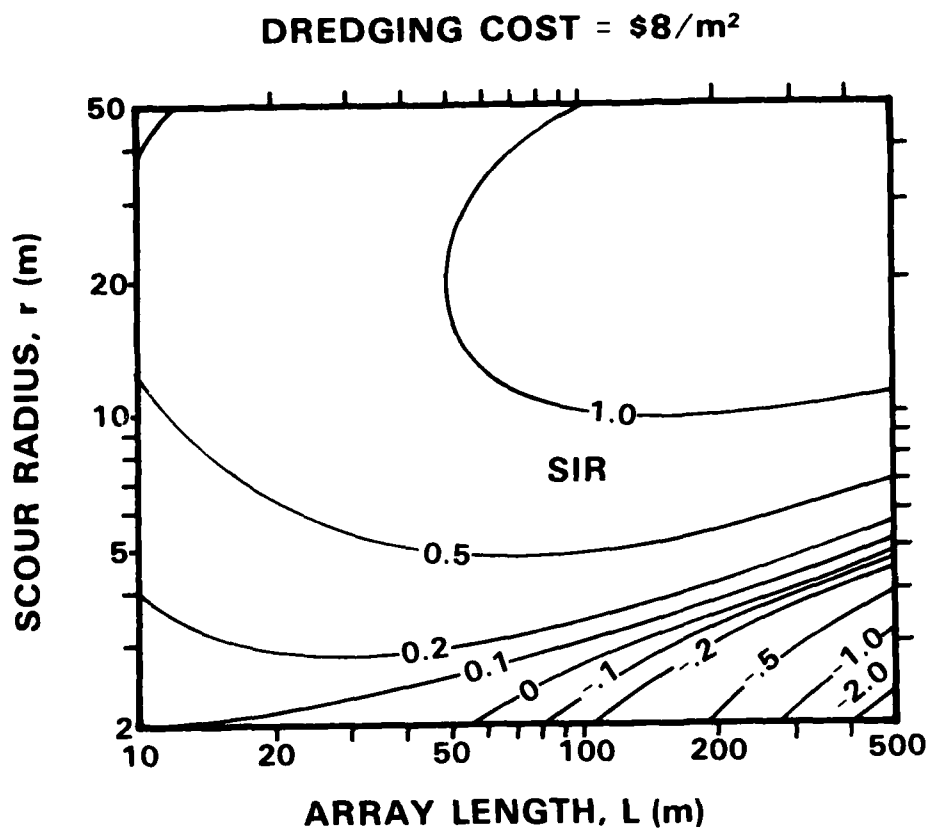


Figure 10. Savings investment ratio as a function of scour radius and array length assuming a dredging cost of \$8/m².

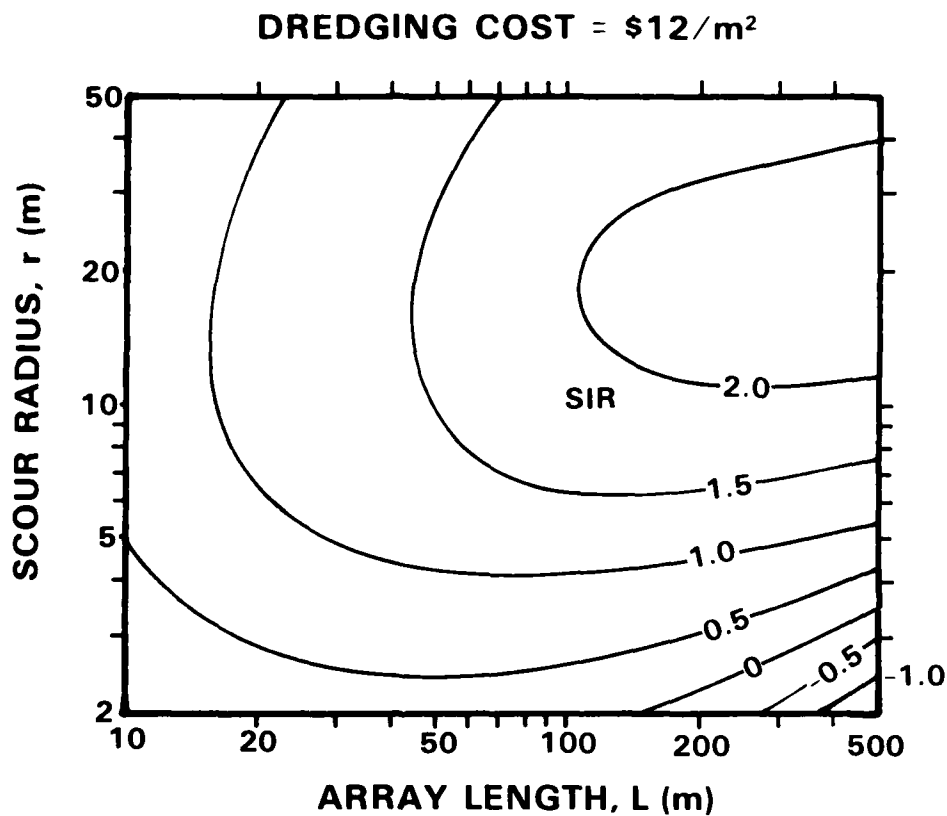


Figure 11. Savings investment ratio as a function of scour radius and array length assuming a dredging cost of \$12/m².

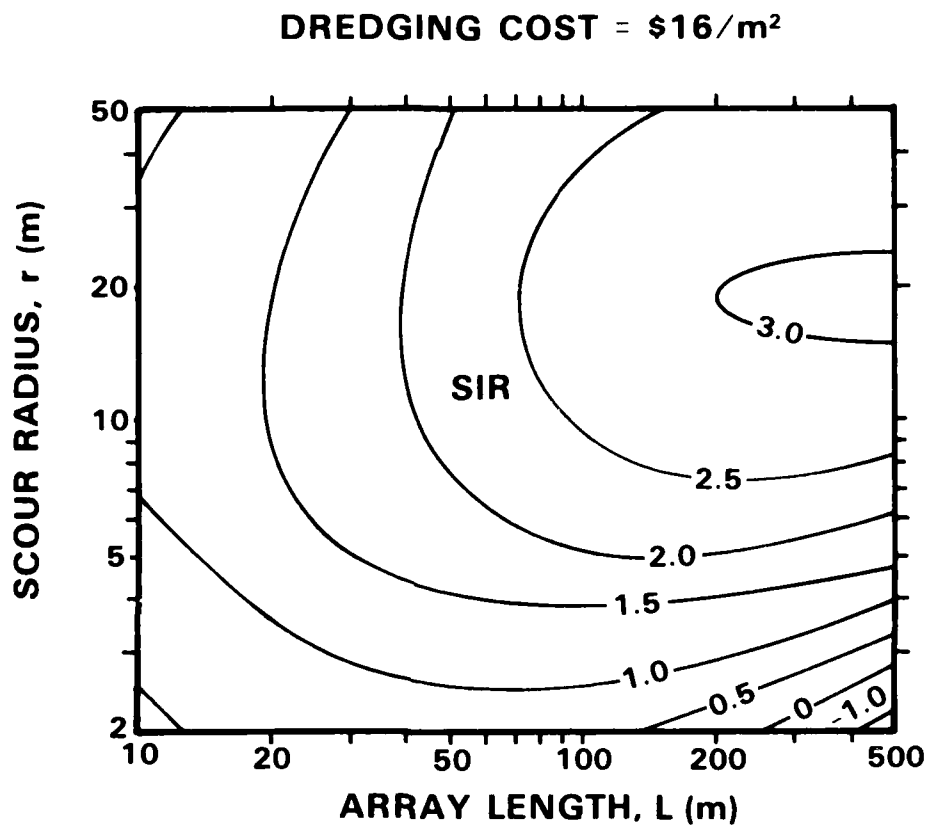


Figure 12. Savings investment ratio as a function of scour radius and array length assuming a dredging cost of \$16/m².

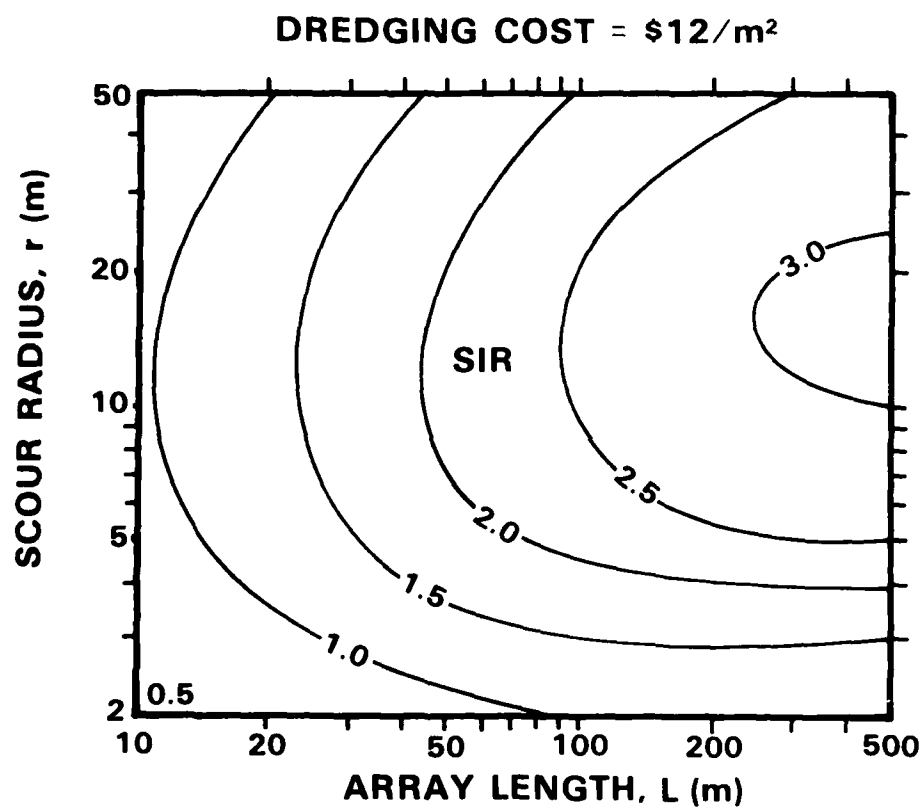


Figure 13. Savings investment ratio as a function of scour radius and array length for conditions at Mare Island Shipyard.

Appendix A

LISTING OF A COMPUTER PROGRAM TO SELECT
AN OPTIMUM SCOUR JET ARRAY

```

100 REM DESIGN OPTIMIZATION OF SCOUR JET ARRAY
110 REM SITE AND SYSTEM INPUTS WHERE
120 REM U=PIPE VELOCITY, M/SEC; N1= SYSTEM LIFETIME, YEARS;
130 REM T1=JET DUTY CYCLE, HOURS; T2=SEDIMENTATION PERIOD, DAYS/YEAR;
140 REM I1=DISCOUNT RATE; I2=DIFFERENTIAL ELECTRICITY INFLATION RATE;
150 REM E1=ELECTRICITY COST, $/KWH; E2=DREDGING COST, $/SM;
160 REM S=SHEAR STRESS ON BOTTOM, NT/SM; L1=DISTANCE FROM WATER TO
170 REM PUMP AND BACK DOWN TO JET, M.
180 U=2.5
190 N1=10
200 T1=0.2
210 T2=244
220 I1=0.1
230 I2=0.03
240 E1=0.025
250 E2=12
260 S=0.4
270 L1=25
280 PRINT "SCHEDULE 80 STEEL PIPE INSTALLED"
290 PRINT "PIPE VEL, M/S; FIXED LENGTH, M; JET TIME, HR; STRESS, NT/SM"
300 PRINT U, L1, T1, S
310 PRINT "SEDIM TIME, DY/YR; SYST LIFE, YR; DISCNT RATE; DIFF EN RATE"
320 PRINT T2, N1, I1, I2
330 PRINT "ELECT COST, $/KWH; DREDGING COST, $/SM"
340 PRINT E1, E2
350 REM CALCULATE PRESENT WORTH FACTOR
360 I3=(1+I1)T1-1)/(I1*(1+I1)T1
370 REM CALCULATE DIFFERENTIAL PRESENT WORTH FACTOR
380 I4=0
390 FOR J=1 TO N1
400 I4=I4+((1+I2)/((1+I1)J))T2
410 NEXT J
420 REM INPUT LENGTH AND SCOUR RADIUS OF ARRAY
430 FOR I=1 TO 100

```

```

440 PRINT "INPUT L, M"
450 INPUT L
460 PRINT "INPUT R, M"
470 INPUT R
480 REM CALCULATE JET SEPERATION AND NUMBER OF JETS
490 L2=R/3.3
500 N2=INT(L/L2)
510 IF N2<1 THEN 530
520 GO TO 540
530 N2=1
540 C1=1.0E+8
550 J1=0
560 FOR J=1 TO 20
570 REM SCAN JET POWER SPACE
580 IF J1=1 THEN 620
590 REM ASSUM JET POWER
600 W1=10↑J
610 GO TO 640
620 W1=10↑(J3+J/10)
630 REM CALCULATE JET FLOWRATE
640 Q=S↑1.43*R↑3.43/(665*W1↑0.429)
650 REM CALCULATE JET PRESSURE DROP
660 P1=W1/Q
670 REM CALCULATE PIPE DIAMETER
680 D1=SQR(4*Q/(3.14*V))
690 REM CALCULATE JET DIAMETER
700 D2=5.34*(Q*Q/P1)↑0.25
710 REM CALCULATE PIPE FRICTION FACTOR
720 R1=V*D1*1000000
730 F=0.01
740 FOR J2=1 TO 3
750 F=(-0.8+2*LOG(R1*SQR(F)))↑-2
760 NEXT J2
770 REM CALCULATE HEADLOSS IN PIPING
780 H1=F*(L/2+L1)*V*V/(D1*2*9.8)

```



```

790 REM CALCULATE MINOR HEADLOSSES
800 H2=(1+0.8+4*0.9)*V*V/(2*9.8)
810 REM CALCULATE TOTAL PRESSURE DROP THROUGH SYSTEM
820 P2=1000*9.8*(H1+H2)+P1
830 REM CALCULATE PUMP HYDRAULIC POWER
840 W2=P2*Q
850 REM CALCULATE OVERALL PUMP-MOTOR EFFICIENCY
860 C2=LGT(W2/746)
870 IF W2/746<1 THEN 920
880 IF W2/746>500 THEN 940
890 C3=1.48*C2-2
900 E=0.5769+0.1528*C3-0.02511*C3+2-0.003951*C3+3
910 GO TO 960
920 E=0.2
930 GO TO 960
940 E=0.8
950 REM CALCULATE POWER OF MOTOR
960 W3=W2/E
970 REM CALCULATE OPERATING TIME PER DAY
980 T3=2*N2*T1
990 REM CALCULATE CAPITAL COST OF SYSTEM
1000 C4=3.64*W2+0.667+0.062*W3+(L+L1)*974*W1+1.09
1010 C4=C4+N2*10366*W1+1.47+1725+295*N2/8
1020 REM CALCULATE PRESENT VALUE OF OPERATING COSTS
1030 C5=W3*T3*T2*E1*I4/1000
1040 REM CALCULATE TOTAL SYSTEM PRESENT VALUE
1050 C6=C4+C5
1060 IF J1=1 THEN 1110
1070 IF J1=2 THEN 1230
1080 IF C6>C1 THEN 1150
1090 C1=C6
1100 GO TO 1190
1110 IF C6>C1 THEN 1200
1120 C1=C6
1130 W4=W1

```

```

1140 GO TO 1190
1150 J1=J1+1
1160 J3=J-2
1170 C1=1.0E+8
1180 GO TO 560
1190 NEXT J
1200 W1=W4
1210 J1=J1+1
1220 GO TO 640
1230 C7=C6/I3
1240 C8=L*R/E2
1250 W5=W3/1000
1260 S1=1+(I4*C8-I3*C7)/C4
1270 PRINT "JET D,M; PIPE D,M; FLO RATE,CM/S; PUMP PR,NT/SM; MTR PWR,KW"
1280 PRINT USING "5(6D.3D3X)":D2,D1,Q,P2,W5
1290 PRINT "CAPITAL COST, ANNUAL COST, SIR"
1300 PRINT C4,C7,S1
1310 NEXT I
1320 END

```

Appendix B

COMPUTER PROGRAM INPUT AND OUTPUT FOR THE
MARE ISLAND NAVAL SHIPYARD EXAMPLE

MARE ISLAND NAVAL SHIPYARD EXAMPLE

SCHEDULE 80 STEEL PIPE INSTALLED			
PIPE VEL, M/S;	FIXED LENGTH, M;	JET TIME, HR;	STRESS, NT/SM
2.5	25	0.2	0.4
SEDIM TIME, DY/YR;	SYST LIFE, YR;	DISCNT RATE;	DIFF EN RATE
244	10	0.1	0.03
ELECT COST, \$/KWH;	DREDGING COST, \$/SM		
0.025	12		
INPUT L, M			
126			
INPUT R, M			
15			
JET D,M; PIPE D,M;	FLO RATE,CM/S;	PUMP PR,NT/SM;	MTR PWR,KW
0.064	0.188	0.069	265288.841
CAPITAL COST, ANNUAL COST, SIR			
54925.8766801	11322.2277139		2.66108988451
INPUT L, M			

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NAVSHIPYD; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, (Woodroff) Norfolk, Portsmouth, VA; Code 400, Puget Sound; Code 400.03 Long Beach, CA; Code 404 (LT J. Riccio), Norfolk, Portsmouth VA; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; L.D. Vivian; Library, Portsmouth NH; PWD (Code 400), Philadelphia PA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Salvage Supt, Phila., PA; Tech Library, Vallejo, CA

NAVSTA CO Naval Station, Mayport FL; CO Roosevelt Roads P.R. Puerto Rico; CO, Brooklyn NY; Dir Mech Engr, Gtmo; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Canal Zone; PWD (LTJG.P.M. Motolenich), Puerto Rico; PWO Midway Island; PWO, Keflavik Iceland; PWO, Mayport FL; ROICC, Rota Spain; SCE, Guam; Utilities Engr Off. (A.S. Ritchie), Rota Spain

NAVSUBASE SCE, Pearl Harbor HI

NAVSUPPACT CO, Seattle WA; Code 413, Seattle WA; LTJG McGarran, SEC, Vallejo, CA

NAVSTA Security Offr, San Francisco, CA

NAVSURFWPCEN PWO, White Oak, Silver Spring, MD

NAVTECHTRACEN SCE, Pensacola FL

NAVUSEAWARENGSTA Keyport, WA

NAVWPNCEN Code 24 (Dir Safe & Sec) China Lake, CA; Code 2636 (W. Bonner), China Lake CA; PWO (Code 26), China Lake CA

NAVWPNSTA Code 092, Colts Neck NJ; Maint. Control Dir., Yorktown VA

NAVWPNSTA PW Office (Code 09C1) Yorktown, VA

NAVWPNSTA PWO, Seal Beach CA

NAVWPNSUPPCEN Code 09 Crane IN

NCBC Code 10 Davisville, RI; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 400, Gulfport MS; NESO Code 251 P.R. Winter Port Hueneme, CA; PW Engrg, Gulfport MS; PWO (Code 80) Port Hueneme, CA

NMCB 5, Operations Dept.

NOAA Library Rockville, MD

NORDA Code 410 Bay St. Louis, MS; Code 440 (Ocean Rsch Off) Bay St. Louis MS

NRI Code 8400 Washington, DC; Code 8441 (R.A. Skop), Washington DC; Rosenthal, Code 8440, Wash. DC

NSC CO, Biomedical Rsch Lab, Oakland CA; Code 54.1 (Wynne), Norfolk VA; Security Offr, Hawaii

NSD SCE, Subic Bay, R.P

NTC Commander Orlando, FL; OICC, CBU-401, Great Lakes IL

NUCLEAR REGULATORY COMMISSION T.C. Johnson, Washington, DC

NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT; Code S332, B-80 (J. Wilcox); Code SB 331 (Brown), Newport RI; Code TA131 (G. De la Cruz), New London CT

OCEANAV Mangmt Info Div., Arlington VA

OCEANSYSLANT LT A.R. Giancola, Norfolk VA

ONR (Dr. E.A. Silva) Arlington, VA; Central Regional Office, Boston, MA; Code 481, Arlington VA; Code 481, Bay St. Louis, MS; Code 700F Arlington VA, Dr. A. Laufer, Pasadena CA

PHIBCB 1 P&E, Coronado, CA
 PMTC EOD Mobile Unit, Point Mugu, CA; Pat. Counsel, Point Mugu CA
 PWC (Lt E.S. Agony) Pensacola, FL; ACE Office (LTJG St. Germain) Norfolk VA; CO Norfolk, VA; CO
 (Code 10), Oakland, CA; CO, Great Lakes IL; Code 10, Great Lakes, IL; Code 110, Oakland, CA; Code
 120, Oakland CA; Code 120C, (Library) San Diego, CA; Code 128, Guam; Code 154, Great Lakes, IL;
 Code 200, Great Lakes IL; Code 200, Guam; Code 220 Oakland, CA; Code 220.1, Norfolk VA; Code 30C,
 San Diego, CA; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code
 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 42B (R. Pascua), Pearl
 Harbor HI; Code 505A (H. Wheeler); Code 600, Great Lakes, IL; Code 601, Oakland, CA; Code 610, San
 Diego Ca; Code 700, Great Lakes, IL; Code 700, San Diego, CA; Utilities Officer, Guam; XO (Code 20)
 Oakland, CA
 SPCC PWO (Code 120) Mechanicsburg PA
 NAF PWO (Code 30) El Centro, CA
 UCT TWO OIC, Norfolk, VA; OIC, Port Hueneme CA
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 US DEPT OF COMMERCE NOAA, Pacific Marine Center, Seattle WA
 US DEPT OF HEALTH, ED. & WELFARE Food & Drug Admin. (A. Story), Dauphin Is. AL
 US DEPT OF INTERIOR Bureau of Land MNGMNT - Code 733 (T.E. Sullivan) Wash, DC
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 US NATIONAL MARINE FISHERIES SERVICE Highlands NY (Sandy Hook Lab-Library)
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 Dowd), Washington DC
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 USDA Forest Products Lab, Madison WI; Forest Service, Bowers, Atlanta, GA
 USNA Civil Engr Dept (R. Erchyl) Annapolis MD; Energy-Environ Study Grp. Annapolis, MD; Environ.
 Prot. R&D Prog. (J. Williams), Annapolis MD; Ocean Sys. Eng Dept (Dr. Monney) Annapolis, MD; PWD
 Engr. Div. (C. Bradford) Annapolis MD; PWO Annapolis MD
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